Microbial and plant-assisted bioremediation of radioactive waste: mechanisms, limits, and applications

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Abstract. Radioactive contamination resulting from nuclear activities, uranium mining, radioactive waste disposal, and nuclear accidents represents a major environmental challenge due to the persistence and toxicity of radionuclides in ecosystems. Bioremediation has emerged as a sustainable and cost-effective alternative to conventional physical and chemical remediation methods. This mini-review presents the main microbial and plant-assisted mechanisms involved in the remediation of radionuclide-contaminated environments. Microbial processes such as biosorption, bioaccumulation, bioreduction, biomineralization, bioprecipitation, and biofilm formation contribute to the immobilization or removal of uranium, cesium, strontium, plutonium, and neptunium. The role of extracellular polymeric substances (EPS) in radionuclide binding and stabilization is also highlighted. In parallel, phytoremediation strategies including phytoextraction, phytostabilization, rhizofiltration, and plant–microbe interactions offer promising approaches for the treatment of contaminated soils and waters. Recent advances in genetic engineering have further enhanced the potential of microorganisms and plants for radionuclide uptake and immobilization. Despite encouraging laboratory and pilot-scale results, several challenges remain regarding field implementation, long-term stability, ecological impacts, and management of contaminated biomass. Overall, the integration of microbial and plant-based technologies represents a promising direction for the sustainable remediation of radioactive waste and contaminated environments.

Keywords: bioremediation, radionuclides, uranium, phytoremediation, biosorption, biofilms, biomineralization, radioactive waste, microorganisms, environmental remediation.

Introduction. Bioremediation of uranium, cesium, strontium and plutonium has emerged as a cost-effective, "green" alternative to physical–chemical cleanup at nuclear sites and in the wake of accidents such as Chernobyl and Fukushima (Banerjee et al., 2022; Kuppusamy et al., 2025). Microbial and plant systems can immobilize, transform, or extract radionuclides, but scale-up, long-term stability, and ecological risks remain major challenges (Thakur & Kumar, 2024; Koul & Adlakha, 2020; López-Fernández et al., 2021; Williamson et al., 2023; Lincoln & Noori, 2025; Li et al., 2022; Newsome et al., 2014; Ammar et al., 2024).

The increasing use of nuclear energy and radioactive materials in medicine, industry, agriculture, and scientific research has led to the generation of significant quantities of radioactive waste worldwide. Improper disposal, accidental releases, and historical nuclear activities have resulted in the contamination of soils, sediments, groundwater, and surface waters with radionuclides that can persist in the environment for decades or even centuries. Due to their radiotoxicity, chemical toxicity, and long half-lives. Radionuclides pose serious risks to ecosystems and human health through direct exposure and through their transfer along food chains (Crăciun et al., 2015; Petrescu-Mag & Oroian, 2015).

Conventional remediation technologies, including excavation, chemical treatment, vitrification, and physical containment, are often expensive and may generate additional waste streams requiring further management. Consequently, considerable attention has been directed toward biological remediation strategies capable of reducing contaminant mobility while minimizing environmental disturbance. Microorganisms and plants have evolved diverse mechanisms that enable them to tolerate, accumulate, transform, or immobilize radionuclides under a wide range of environmental conditions (Deng et al., 2026; Sundar et al., 2023).

Recent advances in environmental microbiology, molecular biology, and biotechnology have improved the understanding of microbial resistance mechanisms, biofilm formation, extracellular polymeric substances, and plant–microbe interactions involved in radionuclide remediation. These developments have opened new opportunities for the design of integrated remediation systems that combine microbial processes with phytoremediation approaches. Nevertheless, several challenges remain regarding field-scale implementation, long-term effectiveness, ecological safety, and the management of contaminated biomass. Therefore, a comprehensive evaluation of the mechanisms, applications, and limitations of microbial and plant-assisted bioremediation is necessary to assess its potential as a sustainable solution for radioactive waste management.

The Purpose of the Paper. The aim of this mini-review is to analyze the current knowledge regarding microbial and plant-assisted bioremediation of radioactive contaminants and to evaluate the mechanisms responsible for radionuclide immobilization, transformation, and removal. The paper focuses on the biological processes involved in microbial biosorption, bioaccumulation, biomineralization, and phytoremediation, while also highlighting recent advances in genetic engineering and microbe–plant interactions. Additionally, the review examines practical applications, ecological limitations, and future perspectives associated with the implementation of biological technologies for the remediation of radionuclide-contaminated environments.

Mechanisms of Microbial Biosorption and Bioaccumulation. Microorganisms interact with radionuclides through biosorption, bioaccumulation, bioreduction, biomineralization, bioprecipitation and biofilm formation (Koul & Adlakha, 2020; López-Fernández et al., 2021; Singh et al., 2022; Newsome et al., 2014; Banala et al., 2020; ElShaarawy, 2024; Rogiers et al., 2022). Cell walls and extracellular polymers provide binding sites (carboxyl, phosphate, hydroxyl) that complex U(VI) and other ions; for example, Deinococcus radiodurans biofilms bind U(VI) via such groups, with sorption following pseudo-second-order kinetics and intra-particle diffusion, yielding uranyl phosphate deposits (Manobala et al., 2020). Redox-active bacteria enzymatically reduce soluble U(VI) to insoluble U(IV), and can also reduce Pu(VI/V) and Np(V), while urease-producing strains promote Sr biomineralization (Newsome et al., 2014; El Shaarawy, 2024; Rogiers et al., 2022). Molecular studies highlight metal efflux systems and resistance genes that underpin uranium tolerance and can be exploited for engineered bioremediation (Koul & Adlakha, 2020; Rogiers et al., 2022) (Table 1).

Table 1

Mechanistic range of microbial processes for key radionuclides

Radionuclide (examples)	*Dominant microbial mechanisms mentioned*	*References*
U, Pu, Np	Bioreduction, biomineralization, biosorption, intracellular accumulation.	López-Fernández et al., 2021; Newsome et al., 2014; Banala et al., 2020; El Shaarawy, 2024; Rogiers et al., 2022
Sr, Cs	Biosorption, biomineralization, biofilm/EPS binding.	Koul & Adlakha, 2020; López-Fernández et al., 2021; Newsome et al., 2014; El Shaarawy, 2024; Shukla et al., 2020.

Role of Biofilms and Exopolysaccharides (EPS). Microbial biofilms and their extracellular polymeric substances can precipitate, concentrate, or immobilize non-degradable radionuclides such as U, Pu and Sr (López-Fernández et al., 2021; Manobala et al., 2020; Shukla et al., 2020). EPS provide dense networks of charged polysaccharides that support sorption and bioflocculation, allowing high local accumulation and potential use in packed-bed or reactor configurations (Manobala et al., 2020; Shukla et al., 2020; Balíková et al., 2022). In U(VI) systems, biofilm biomass not only adsorbs uranium but also drives formation of low-solubility uranyl phosphates, linking EPS chemistry, phosphatase activity and long-term immobilization (Newsome et al., 2014; Manobala et al., 2020; Shukla et al., 2020). Although much EPS work is on heavy metals, similar sorptive interactions and flocculation principles are directly applicable to radionuclide-contaminated effluents (Shukla et al., 2020; Balíková et al., 2022).

Phytoremediation, Hyperaccumulators and Genetic Engineering. Phytoremediation uses phytoextraction, phytostabilization, rhizofiltration, phytovolatilization and phytostimulation to manage U, Cs, Sr, Pu and other radionuclides in soils and waters (Koul & Adlakha, 2020; Williamson et al., 2023; Lincoln & Noori, 2025; Li et al., 2022; Ali et al., 2023; Singh et al., 2022; Ammar et al., 2024; Singh et al., 2021; Kafle et al., 2022) (Table 2, Figure 1). Hyperaccumulator plants, including aquatic species such as Fontinalis antipyretica that can reach ~5000 mg U kg^{-1} dry mass, illustrate the capacity for extreme uranium uptake (Thakur & Kumar, 2024; Akash et al., 2022; Singh et al., 2022). For Cs-137 and Sr-90, plant uptake is shaped by species, root architecture, soil texture, competing ions and agronomic practices; intercropping, chelating agents (e.g. citric acid) and soil amendments (biochar, organic matter, humic substances) can significantly enhance extraction (Williamson et al., 2023; Singh et al., 2022; Li et al., 2022; Ammar et al., 2024; Singh et al., 2021; Kafle et al., 2022).

Genetically engineered microbes and plants expressing specific metal transporters, phosphatases and reductases (e.g. NiCoT, phoK, DrPhoN, mer and czc systems) are proposed to increase radionuclide uptake or immobilization, and microbe–plant consortia may provide synergistic removal in the rhizosphere (Koul & Adlakha, 2020; Li et al., 2022; El Shaarawy, 2024; Rogiers et al., 2022). However, most such strategies remain at laboratory or pilot scale.

Table 2

Main plant-based remediation modes relevant to nuclear contaminants

Mode / example	*Target & outcome (qualitative)*	*References*
Phytoextraction (shoot harvest)	High U, Cs, Sr removal with hyperaccumulators, long time scales	Thakur & Kumar, 2024; Akash et al., 2022; Williamson et al., 2023; Singh et al., 2022; Ammar et al., 2024; Singh et al., 2021; Kafle et al., 2022
Rhizofiltration / rhizostabilization	Immobilization/uptake from water and rhizosphere, reduced leaching	Koul & Adlakha, 2020; Williamson et al., 2023; Lincoln & Noori, 2025; Ali et al., 2023; Singh et al., 2022
Enhanced by amendments / GM	Increased bioavailability or transport using chelators, engineered transporters	Koul & Adlakha, 2020; Williamson et al., 2023; Li et al., 2022; Ammar et al., 2024; Singh et al., 2021; Rogiers et al., 2022; Kafle et al., 2022.

Field Applications, Ecological Limits and Trophic Risks. Field-scale microbial biostimulation at uranium-contaminated sites has achieved sustained U(VI) removal via bioreduction and phosphate biomineralization, but rebound in mobility can occur due to reoxidation, changing redox conditions, competing electron acceptors (e.g. nitrate) and co-contaminant metals that inhibit key pathways (Williamson et al., 2023; Newsome et al., 2014; Rogiers et al., 2022). Deep geological repositories will also be influenced by microbial processes, yet real-world applications remain at an early stage, with complex pH, ion chemistry and life-cycle constraints limiting predictability (López-Fernández et al., 2021; Williamson et al., 2023).

For Chernobyl-like and Fukushima-type landscapes, phytoremediation is attractive but not yet sufficient alone; decades after Chernobyl, residual Cs and Sr remain, and no single remediation method has fully resolved contamination (Singh et al., 2022; Lincoln & Noori, 2025; Ali et al., 2023). Persistent radionuclides can enter food webs through crops and forage, driving phytotoxicity and risks of biomagnification, so removal must be balanced with safe management of contaminated biomass and prevention of re-entry into the trophic chain (Williamson et al., 2023; Ali et al., 2023; Singh et al., 2022; Ammar et al., 2024; Singh et al., 2021). Disposal or valorization options for harvested biomass (e.g. energy, sorbent production) are being explored to close the loop and minimize secondary waste (Williamson et al., 2023; Singh et al., 2022; Singh et al., 2021).

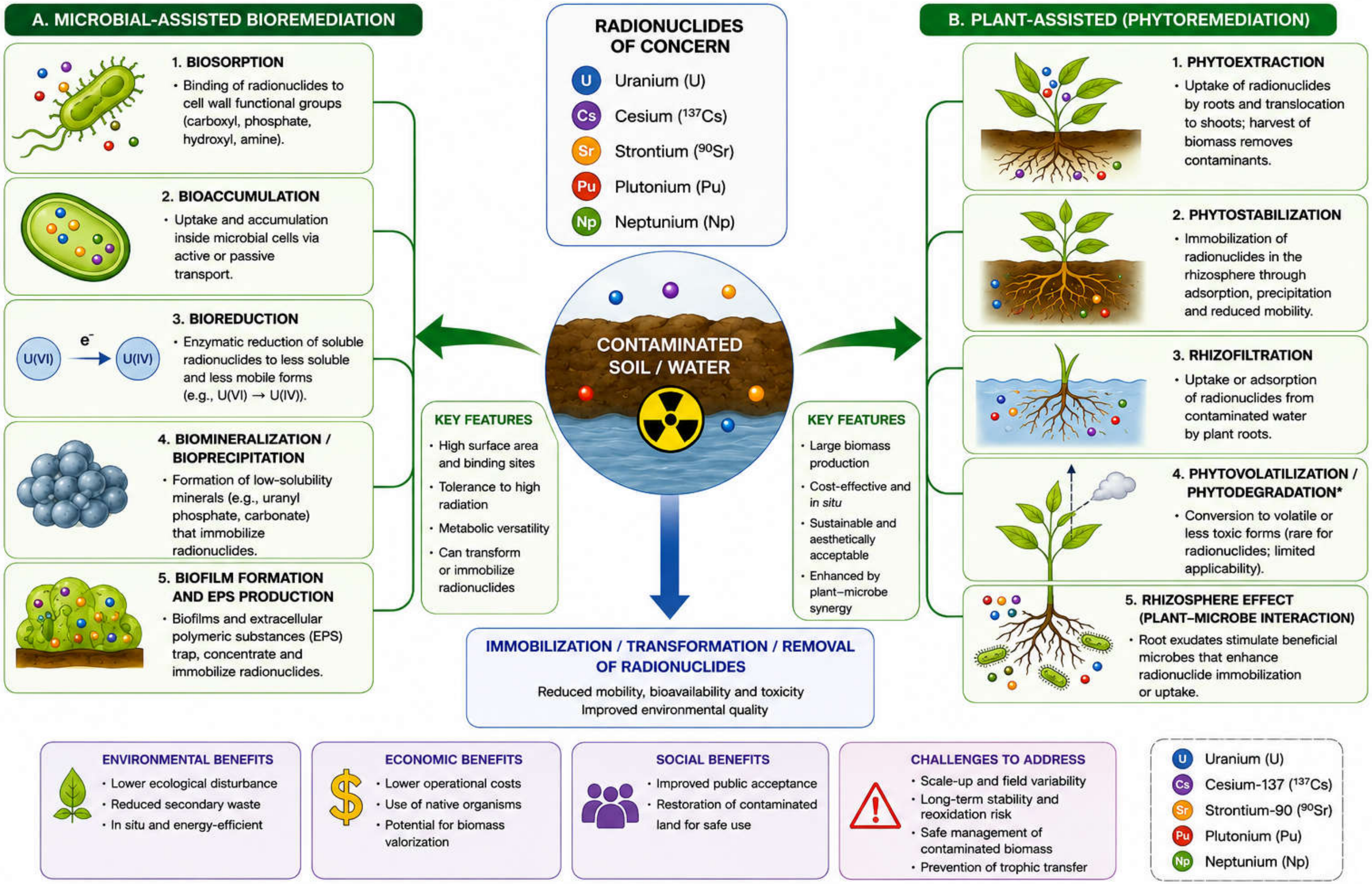

Figure 1. Overview of microbial and plant-assisted mechanisms for the bioremediation of radionuclide-contaminated environments.

Conclusions. Microbial and plant-assisted bioremediation has emerged as a promising and sustainable approach for the remediation of radionuclide-contaminated environments. Microorganisms can immobilize or transform radionuclides through processes such as biosorption, bioreduction, biomineralization, and biofilm formation, while plants contribute through phytoextraction, phytostabilization, and rhizofiltration. Recent advances in biotechnology and plant–microbe interactions have further expanded the potential of these remediation strategies. However, challenges related to field-scale implementation, long-term stability, and ecological safety still limit their widespread application. Future research should focus on improving remediation efficiency and ensuring the safe management of contaminated biomass. Overall, the integration of microbial and plant-based technologies represents a valuable tool for the sustainable management of radioactive contamination.

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Conflicts of Interest. The author declares that there is no conflict of interest.

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